Ultra Low Reflectivity Black Silicon Surfaces and Devices Enable Unique Optical Applications

Karl Yee

Victor White, Kunjithapatham Balasubramanian, Daniel Ryan

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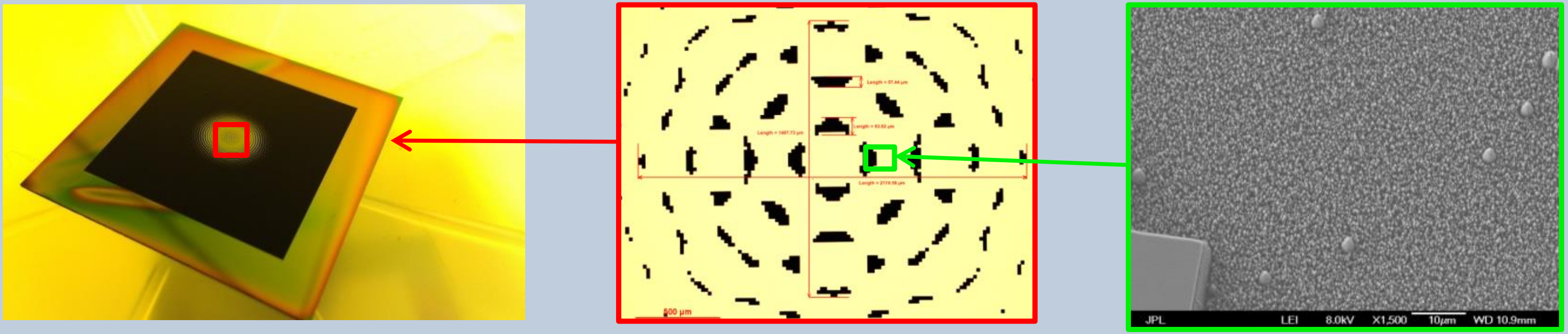
Black Silicon Description

“Black silicon” is a surface texturing of a silicon substrate, resulting in a surface with low reflectivity of visible/IR radiation.

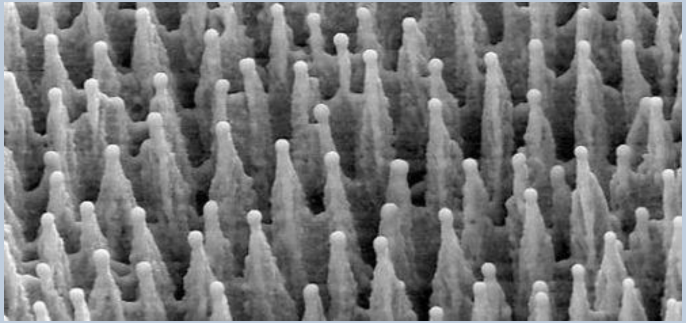


Example: Coronagraph mask with patterned black regions formed by black silicon

Properties

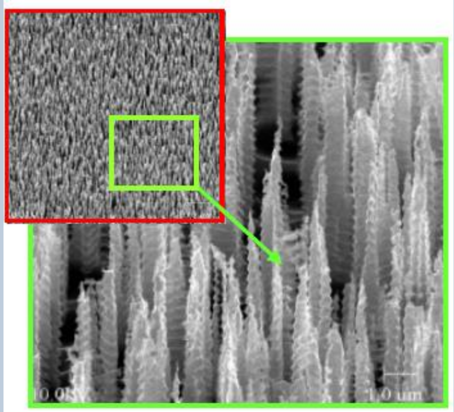
- Greatly enhanced surface area (applications: capacitors, batteries, gas sensors)
- Super hydrophobic surface (can be made hydrophilic with surface coating or oxidation) (applications: fluidic devices, thermal management)
- Optically black surface (applications: stray light elimination, high contrast imaging, bolometers, solar cells)

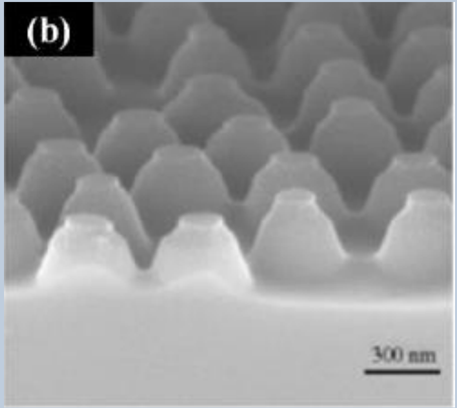
Examples of Black Silicon Formation Techniques



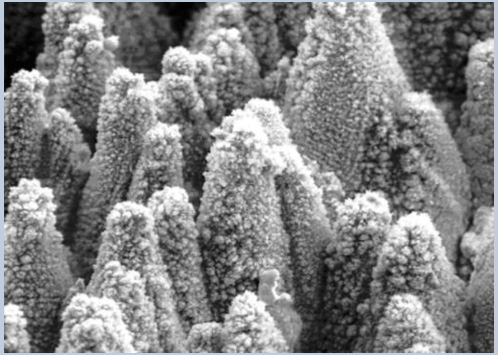
Silicon substrate exposed to high intensity laser pulses in the presence of SF_6 (SiOnyx)

Bosch etch (cyclic switching between a near isotropic etch and passivation) with micro masking produced through over passivation (JPL)





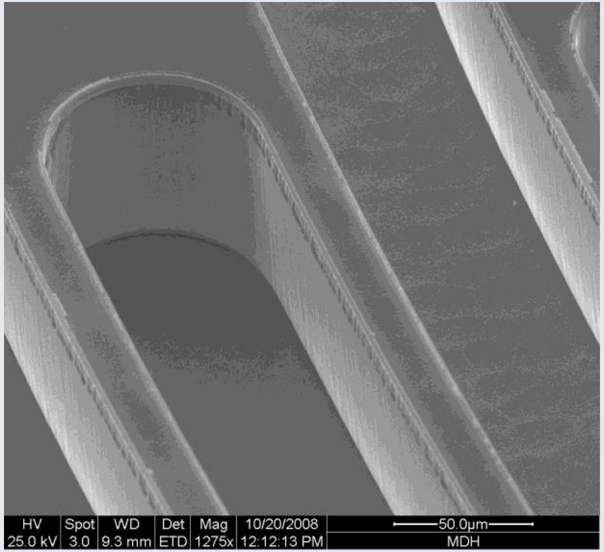
Silicon nanopillars formed by reactive ion etching through a mask of polystyrene spheres (Korea Univ. of Science and Technology)



Reactive ion etching of Si in CCl4 and HCl plasmas (General Electric)

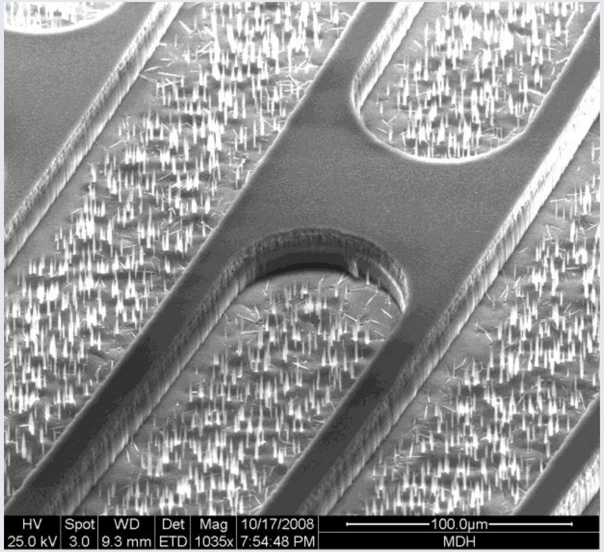
Cryo Etched Black Silicon

Formation process: Oxygen combines with SF_6 + Si etch byproducts to form a passivation layer atop the Si when the etch is performed at cryogenic temperatures. Excess flow of oxygen results in micro masking, enabling the formation of black silicon.

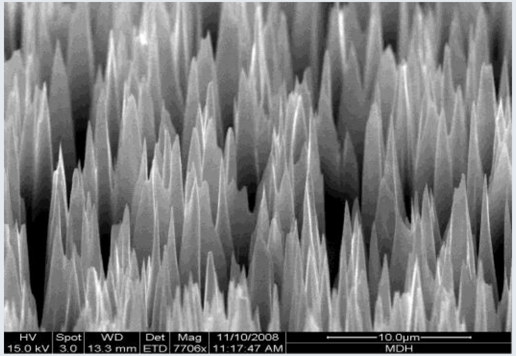


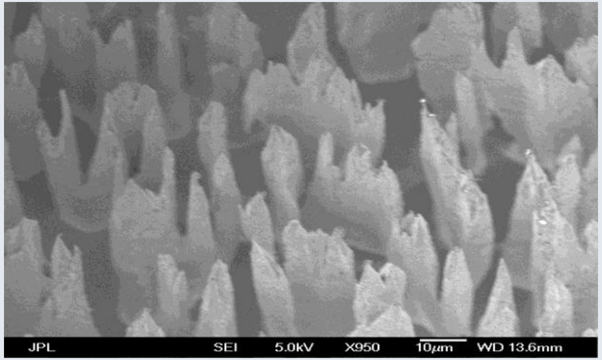
Anisotropic cryo etched structure

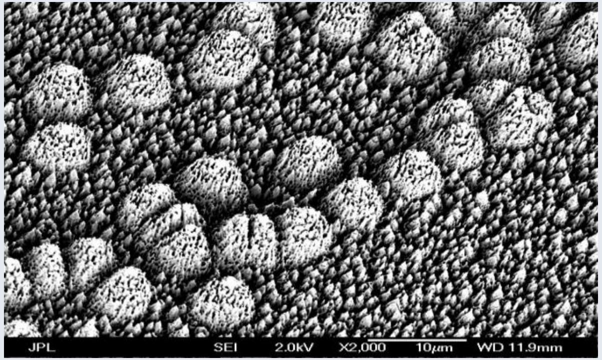
Identical mask, but excess O_2 flow utilized, resulting in the formation of black silicon



Characteristics of Cryo Etched Black Silicon



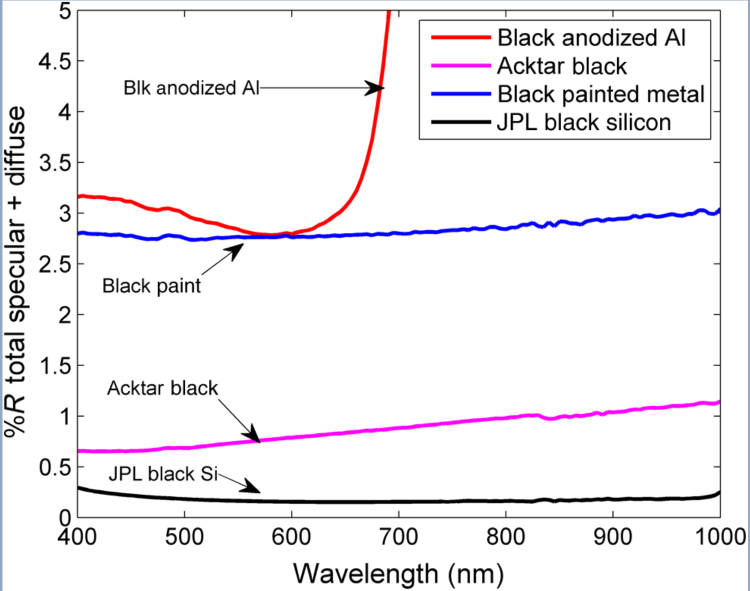




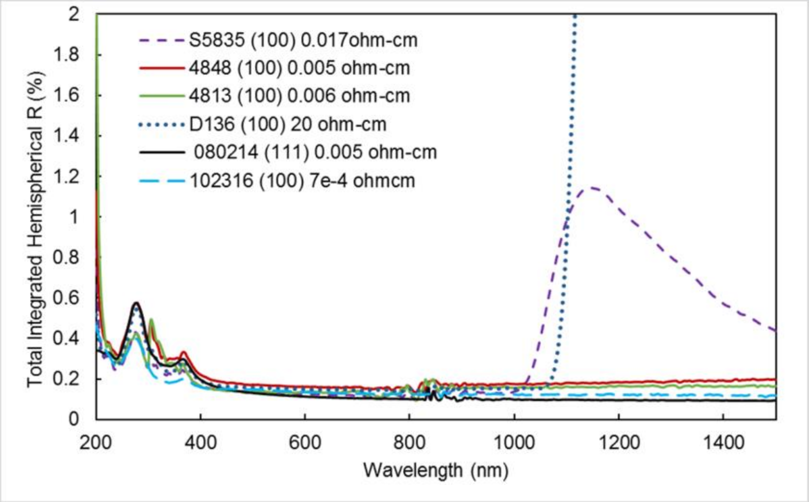
Characteristics of cryo etched black Si:

- **Cryo etch blackening process is rapid and repeatable**
- **Blackened regions definable with lithographic precision over large areas**
- **Compatible with arbitrary doping level of silicon**
- **Robust, non-outgassing textured surface compatible with wet processing**
- **Process parameters can be adjusted for control over average height (1 – 150 μm), spacing of needles and morphology**

Black Silicon Reflectance



Comparison of measured total integrated reflectance (specular + diffuse) of various materials



Reflectance minimized out to longer wavelengths (>20μm) through use of highly doped silicon

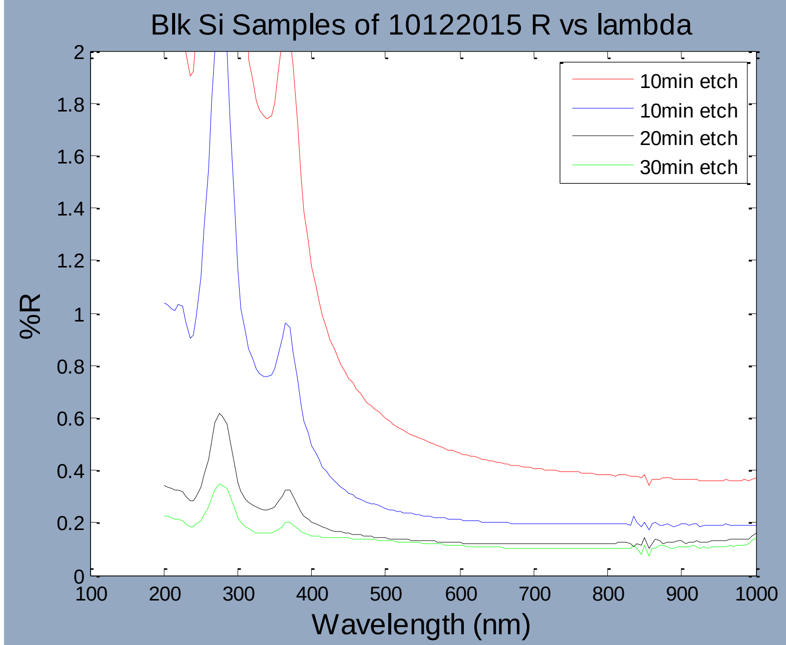
Cryo Etched Black Silicon Etch Parameters

Parameters that determine etch characteristics:

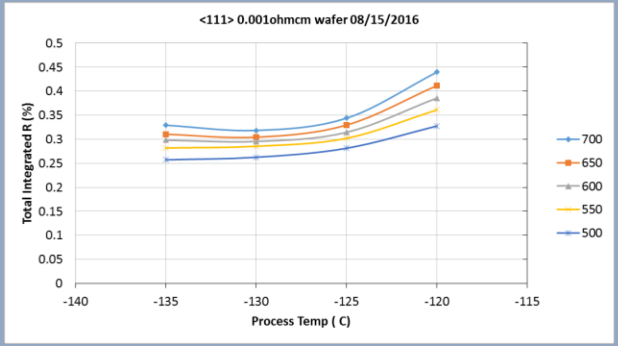
- SF_6 flow rate – primarily affects ion F density
- O_2 flow rate – increases passivation; over passivation leads to micro masking, enabling black Si formation
- ICP power – increases ion density
- Forward power – affects etch depth; also removes passivation layer
- Chamber pressure – increases ion density
- Chamber temperature – enables formation of passivation layer; over passivation results in micro masking, enabling black Si formation
- Etch duration – affects etch depth

= parameters that have largest effect on formation of black silicon

Reflectance Dependence on Etch Parameters



Reflectivity is a monotonic function of etch time

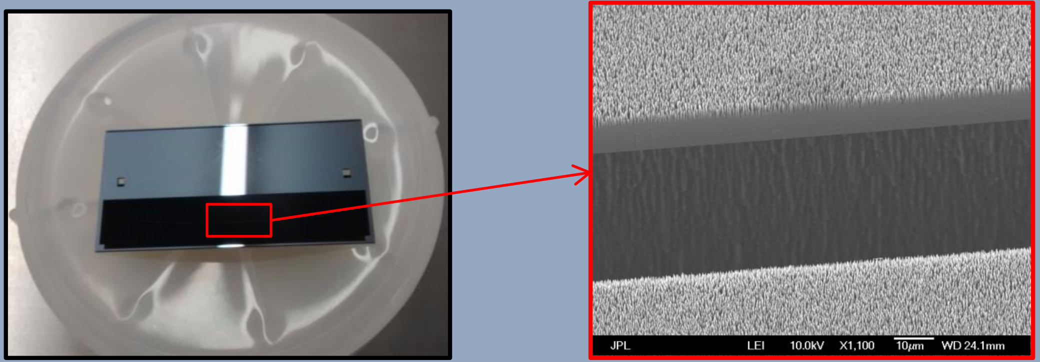


- Lower ICP power (i.e. ion density) results in lower reflectivity (up to a point)*
- Reflectivity is increases rapidly with temperature*

*Optimal values strongly dependent on set of all 7 etch parameters

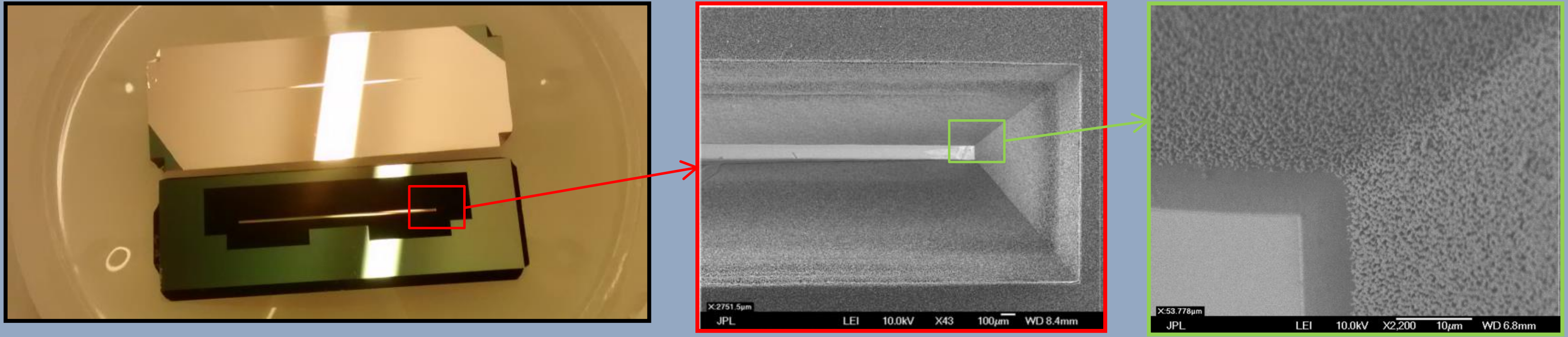
Application: Optical / IR Black

Imaging Spectrometers



Flat geometry slit

Stray light falsely increases the signal at some wavelengths. Black silicon absorption of stray light reduces signal distortion.



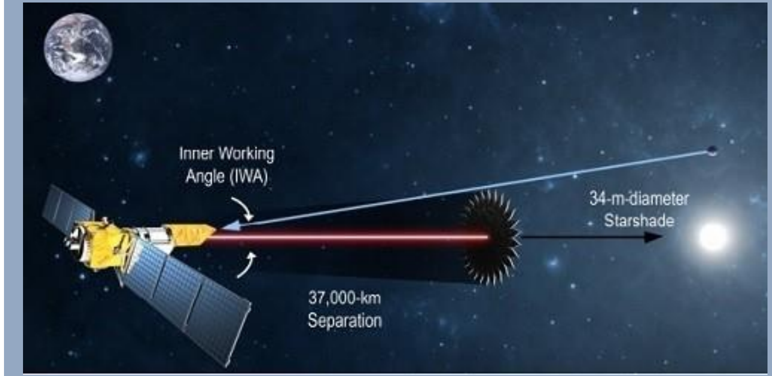
V-groove geometry slit

Application: Optical / IR Black

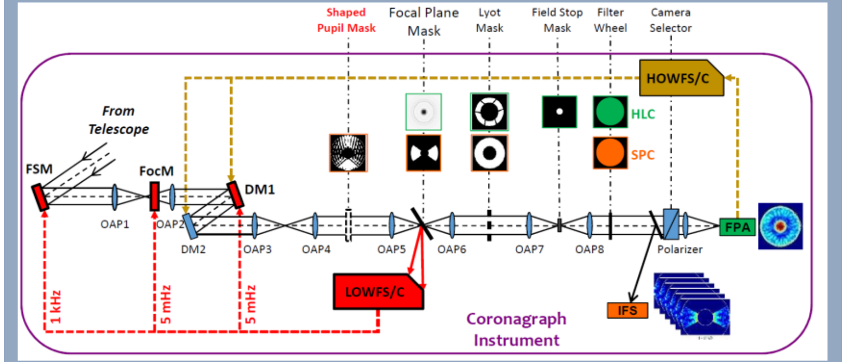
Coronagraph Masks (1)

Imaging an exoplanet requires occultation of the parent star, and suppression of diffracted light from the star:

This can be accomplished with an external occulter (e.g. a Starshade):



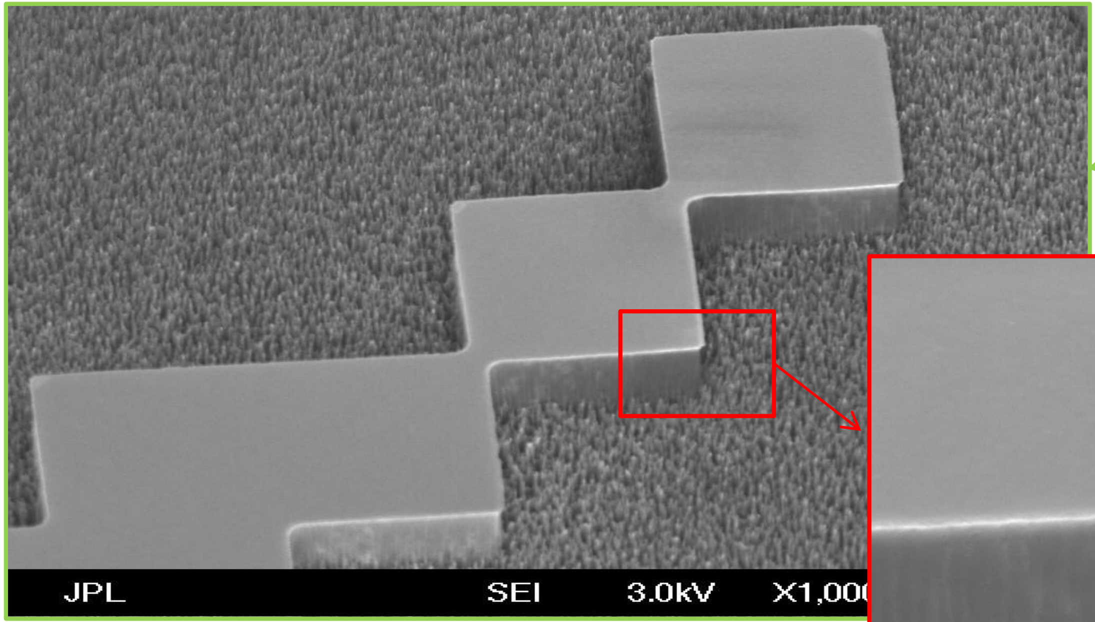
… or with an internal occulter (e.g. a coronagraph):

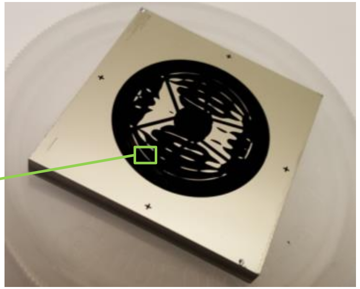


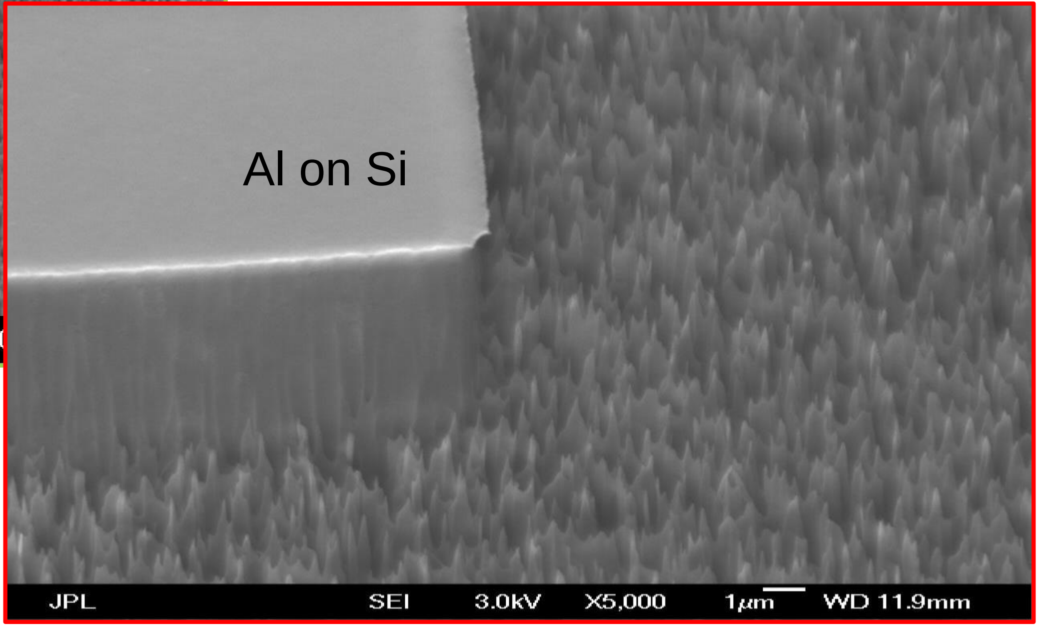
Black silicon is being used for diffracted light absorption on the reflective shaped pupil masks in the Wide-Field Infrared Space Telescope (WFIRST).

Application: Optical / IR Black

Coronagraph Masks (2)



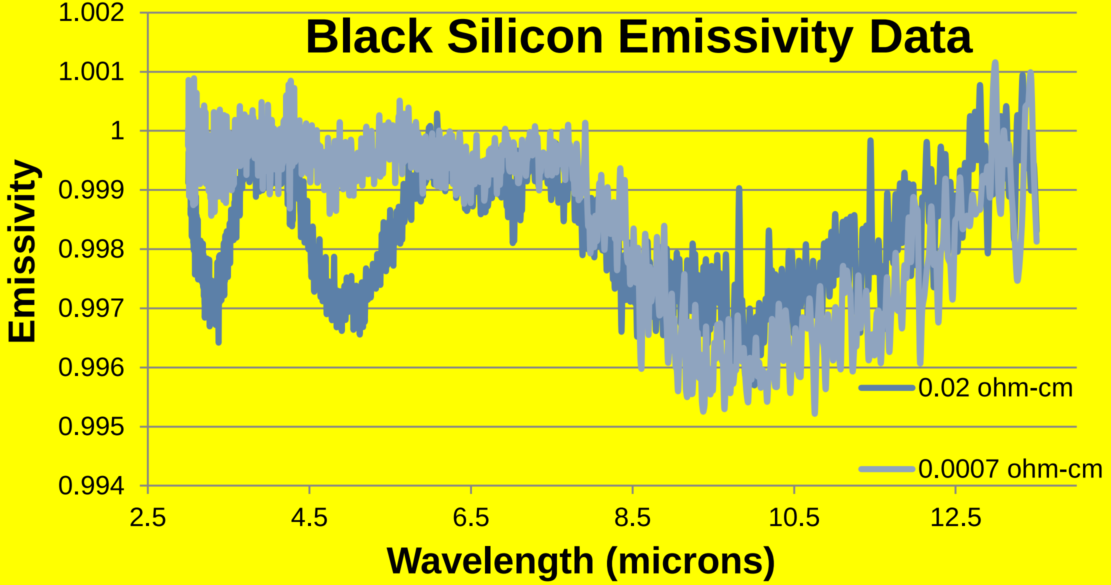




- Micro structured black silicon specular reflectivity: $R < 10^{-7}$
- Diffuse reflectivity: $R \sim 0.1\%$

Application: High Emissivity Surface

Blackbody Calibration Source



Black silicon emissivity data for samples with two different resistivities .

JPL black Si emissivity comparison with commercial coatings:

Coating type	Emissivity (3-30μm)
JPL black silicon	> 0.995
Acktar Ultra Black	> 0.93
Acktar Fractal Black	> 0.88
Actar Magic Black	> 0.75

Black Silicon blackbody calibration targets will be used on:

- **ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)**
- **CubeSat Infrared Atmospheric Sounder (CIRAS)**

Conclusions

- Devices utilizing black silicon are a continuing, active area of research at JPL
- Some of the properties of black silicon being utilized include:
  - Low reflectivity
  - High emissivity
  - Surface area enhancement
  - Super hydrophobicity / super hydrophilicity
- Flight instruments incorporating black silicon devices include: WFIRST, ECOSTRESS, CIRAS, HyTES, AVIRIS, UCIS, HyspIRI, MaRS2, PRISM, NEON, SWIS
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